Can the bosonic coupling constant be extracted from the ARPES scattering rate in cuprate superconductors?

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The recent ARPES results for the imaginary part of the self-energy $\Sigma''(\omega,T)$ obtained on a number of HTSC bismuthates [1] are analyzed. By accepting the "Fermi-Bose" *division-procedure* of $\Sigma''(\omega,T)$ into the Fermi-liquid and bosonic parts - which is proposed in [1], one obtains very small bosonic coupling constant $\lambda_{B,Im}<0.2$. If this procedure would be correct then the standard Eliashberg theory makes any bosonic mechanism of pairing irrelevant! As a consequence we are *confronted with a trilemma*: (1) to abandon the "Fermi-Bose" division-procedure [1]; (2) to abandon the Eliashberg theory; (3) to abandon the interpretation of ARPES data within the three-step model, where the ARPES intensity is proportional to the quasiparticle spectral function $A(\mathbf{k},\omega)$. However, since the bosonic coupling constant extracted from the ARPES nodal kink at 70 meV [2], which measures the real part of the self-energy $\Sigma'(\omega,T)$, is much larger than the one extracted from the ARPES line-width ($\lambda_{B,Im}\ll\lambda_{B,Re}>1$) this means that the "Fermi-Bose" division procedure done in [1] is ambiguous.

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Recently, very interesting results were reported on ARPES measurements in a number of HTSC compounds [1], such as the superstructure free $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$ $(Bi(Pb)-2212)$, $Bi_2Sr_2CaCu_2O_{8+\delta}$ $(Bi-2212)$ and $Bi_2Sr_{2-x}La_xCu_2O_{8+\delta}$ $(Bi-2201)$. By measuring the width $(\Delta k_{FW}(\omega))$ of momentum distribution curves (MDCs) in the *nodal direction* the authors of [1] were able to extract the imaginary part $\Sigma''(\omega,T)$ of the quasiparticle self-energy $\Sigma(\omega,T)(=\Sigma'(\omega,T)+i\Sigma''(\omega,T))$ by using the relation $\Sigma''(\omega,T)\approx v_F\Delta k_{FW}(\omega)/2$ with $\hbar v_F=4\ eV\mathring{A}$ [1].

Let us discuss the results for $\Sigma''(\omega)$ in the *nodal direction* obtained in [1] which are presented in Fig.1 (which is also Fig.1 in Ref. [1]). In [1] the experimental results are analyzed by assuming that the "Fermi-Bose" division of $\Sigma''(\omega,T)$ holds, i.e. there is a Fermi-part due to the Landau-Fermi liquid $\Sigma''_F(\omega,T)$ and the Bose-part due to the scattering via the boson channel $\Sigma''_B(\omega,T)$ [1]. We show below that experiments in Ref. [1] give evidence for the significant contribution of the impurity scattering to $\Sigma(\omega,T)$, which we also take into account. In that case the self-energy is given by

$$\Sigma''(\omega,T)=\Sigma''_F(\omega,T)+\Sigma''_B(\omega,T)+\Sigma''_{imp}(\omega,T). \qquad (1)$$

The Fermi part is given approximately by

$$\Sigma''_F(\omega,T)\approx A_\omega\omega^2+A_T\pi^2T^2, \qquad (2)$$

where it is expected that like in the isotropic Landau-Fermi liquid one has

$$A_\omega\approx A_T. \qquad (3)$$

In the inset of Fig.1a the authors in [1] determine $\Sigma_F(\omega,T)$ by fitting the data in the highly overdoped sample ($OD69$ with $T_c=69\ K$) at $T=130\ K$ by $Eq.(1)$. Unfortunately, the authors in [1] do not report the value for A_ω. Let us determine $A_\omega=[\Sigma''(\omega,T)-\Sigma''(\omega=0,T)]/\omega^2$ from the data in Fig.1a, i.e. from the data for $OD69$ at $T=130\ K$. From the *inset* in Fig.1a one has $\Sigma''_{\exp}(\omega=0,130K)\approx 0.06\ eV$ and $\Sigma''(\omega=0.3,130K)\approx 0.25\ eV$ what gives a reasonable value $A_\omega\approx 2/eV$. ω is given in eV.

Since the authors of [1] do not estimate the contribution of impurities $\Sigma''_{imp}(\omega,T)$ let us do it here. The latter contribution is appreciable since from the inset in Fig.1 one has that $\Sigma''_{imp}(\omega=0,T)(=\Sigma''_{\exp}(0,T)-\Sigma''_F(0,T)-\Sigma''_B(0,T))$ is large fraction of $\Sigma''_{\exp}(0,T)$. The term $\Sigma''_{imp}(\omega=0,T)$ can be extracted (in a semi-quantitative way) by considering the experimental results for $\Sigma''(\omega=0,T)(\gtrsim\Sigma''_{imp}(0,0))$ at $T\ll T_c$. By taking the data from Figs.(1-3) in [1] for $T\ll T_c$, we conclude that for a number of systems with $T_c=(60-90)$ K one has

$$\Sigma''_{imp}(\omega=0,T\ll T_c)\approx(0.02-0.03)eV. \qquad (4)$$

Let us analyze the effect of impurities on T_c. Before doing this, we stress that in the systems which are studied in [1] d-wave pairing is realized. If one assumes that the standard Eliashberg theory holds and that $\Sigma''_{imp}(0,0)$ is momentum independent, i.e. it contains the s-wave scattering channel only $\Sigma''_{imp}(0,0)\approx\Sigma''_{imp,s}(0,0)$, then this isotropic impurity scattering is strongly pair-breaking for d-wave pairing. Since in T_c is smaller than the bare $T_{c,0}$ (for the clean system), then the interesting question is how big is $T_{c,0}$? The theory [3] predicts the following formula for T_c in the case when there is the *s-wave impurity channel* only

$$\ln\frac{T_c}{T_{c0}}=\psi(\frac{1}{2})-\psi(\frac{1}{2}+\rho^s_{pb}), \qquad (5)$$

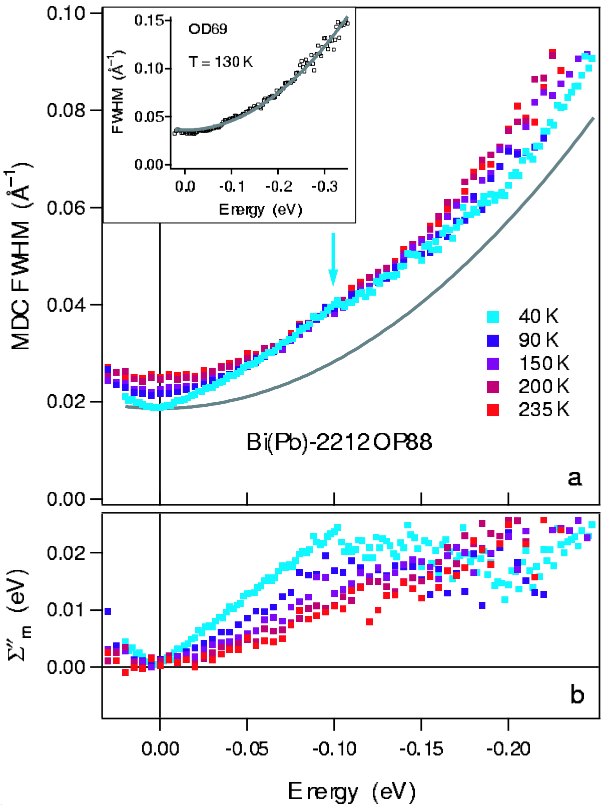

FIG. 1: T- and ω-dependence of Σ'' for the nodal quasiparticles in optimally doped Bi(Pb)-2212. (**a**) - the full width at half maximum of the ARPES intensity. The gray solid line is the Fermi liquid parabola obtained by fitting the data for highly overdoped sample (OD69) at 130 K (see inset). (**b**) - the bosonic part Σ''_B for various T.From [1]

where the pair-breaking parameter $\rho^s_{pb} =\mid \Sigma''_{imp,s} \mid /2\pi T_c$. By taking the values for $\Sigma''_{imp,s}$ from Eq.(3) one obtains $T^{OD}_{c0} = (115 - 150)\ K$ with $T^{OD}_c = 69\ K$ for the *overdoped* SC, and for the *optimally doped* $T^{OP}_{c0} \approx (130-160)\ K$ with $T^{OP}_c \approx 90\ K$. However, this analysis might be inappropriate for HTSC, which are strongly correlated materials and which show surprising robustness of d-wave pairing in the presence of non-magnetic impurities when the dependence $T_c(\rho_{imp})$ is studied. Here, ρ_{imp} is the residual resistivity - see more in Ref.[3]. The theory of the impurity scattering in strongly correlated systems done in [4], and which is based on the theory of strong correlations [5], shows the existence of the forward scattering peak in the scattering amplitude. The latter gives rise to the pronounced *d-wave impurity scattering channel* $\Sigma''_{imp,d}$, thus lowering the impurity pair-breaking effects since in that case $\rho_{pb} =\mid \Sigma''_{imp,s} - \Sigma''_{imp,d} \mid /2\pi T_c$. For a further analysis of the impurity effect on T_c the experimental data for $T_c(\rho_{imp})$ are necessary.

The large values of T_c (and T_{c0}) need also a large bosonic coupling constant $\lambda_B \approx 2$ in the Eliashberg theory. In that respect one can rise an important question - *how large is the bosonic coupling constant* λ_B *extracted from the ARPES line-width measurements in [1]*? In absence of a reliable microscopic theory for HTSC oxides one can proceed by using a phenomenological approach to analyze the ARPES data. From Fig.1b (also Fig.1b in [1]) we see that the bosonic part of $\Sigma''_B(\omega)$ is linear in ω at low T, similarly as in the "marginal" Fermi liquid where $\Sigma''_B(\omega) \approx (\pi/2)\lambda_{B,Im}\omega$. From the values of $\Sigma''_B(\omega)$ at energies $\omega > 0.05eV$ - where the self-energy is weakly affected by superconductivity, which we extract from the top curve in Fig.1b for the optimally doped SC with $T_c = 88\ K$ and at $T = 40\ K$, one obtains a conservative value $\lambda_{B,Im} < 0.2$! Note, that the curve at $T = 90$ K (slightly above T_c!) in Fig.1b of Ref. [1] - below the top one, gives even smaller $\lambda_{B,Im}$! Such a small (bosonic) coupling constant ($\lambda_{B,Im} < 0.2$) gives very small $T_c (\ll 100\ K)$ already for s-wave pairing. in the standard Eliashberg theory. This means that if the "Fermi-Bose" division in [1] would be appropriate than *all bosonic mechanisms of pairing (EPI, SFI,etc.) would be ineffective and irrelevant in cuprate superconductors*!

As a consequence we are *confronted with a trilemma*: (**1**) to abandon the "Fermi-Bose" division-procedure from [1]; (**2**) to abandon the Eliashberg theory; (**3**) to abandon the interpretation of ARPES data within the three-step model, where the ARPES intensity is proportional to the quasiparticle spectral function $A(\mathbf{k},\omega) = -\Im G(\mathbf{k},\omega)/\pi$? It seems that the case (**1**) is most probable. The argument for this claim is based on the ARPES measurements of the real part of the self-energy $\Sigma'(\omega)$. The latter [2], [6], [7] show *kink* in the nodal quasiparticle energy at the phonon energies $\omega \approx 60 - 70\ meV$, which gives the coupling constant $\lambda_{B,Re} =\mid \partial\Sigma'/\partial\omega \mid > 1$. The latter coupling is most probably due to the pronounced *electron-phonon interaction* in HTSC [3]. The above analysis shows that $\lambda_{B,Im} \ll \lambda_{B,Re}$ thus questioning the "Fermi-Boson" division procedure done in Ref.[1], which gives $\lambda_{B,Im} < 0.2$. However, the cases (**2**)-(**3**) might interfere too.

In fact, if (i) the (bosonic-like) spin-fluctuation scattering would be the dominant one - as it is claimed in [1], and (ii) if the "Fermi-Bose" division of Ref.[1] holds, then the ARPES results in [1] tell us that (because $\lambda_{B,Im} \ll 1$) the spin-fluctuation scattering mechanism is irrelevant for pairing in cuprate superconductors. We stress that, there are other reliable arguments against the spin-fluctuation pairing mechanism and which are in favor of the electron-phonon interaction Refs.[3], [8], [9].

Finally, we stress, that the small value of the bosonic coupling constant $\lambda_{B,Im}$, which is extracted from Σ''_{ARPES} for $\omega > 0.05\ eV$, is common to all ARPES measurements [7]. For instance, in the very recent ARPES measurements of the scattering rate in optimally and highly overdoped Bi2212 and Bi2201 compounds [10] it was found that $\Sigma''_{ARPES}(\mathbf{k},\omega) = a_{\mathbf{k}} + b_{\mathbf{k}}\omega$ with $a_{\mathbf{k}}$ strongly momentum dependent while $b_{\mathbf{k}} \approx const = b$ is isotropic. By taking again $v_F \approx 4\ eV\mathring{A}$ we obtain $b \approx 0.4$ and $\lambda_{B,Im} \approx 0.3$. It is hardly to belive that such a small $\lambda_{B,Im}$ can give $T_c \approx 100\ K$ in the Eliashberg

theory. Therefore, the analysis of the ARPES scattering rate solely by the marginal Fermi liquid phenomenology is inadequate and the electron-phonon interaction must be inevitable taken into account. More on that see in Refs. [9], [11].

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